The LSND/MiniBooNe excess events and heavy neutrino from μ and K decays

S.N. Gninenko Institute for Nuclear Research, Moscow 117312 (Dated: May 9, 2011)

It has been recently shown that puzzling excess events observed by the LSND and MiniBooNE neutrino experiments could be interpreted as a signal from the radiative decay of a heavy sterile neutrino (ν_h) of the mass from 40 to 80 MeV, with a muonic mixing strength $|U_{\mu h}|^2 \simeq 10^{-3} - 10^{-2}$, and the lifetime $10^{-11} \lesssim \tau_h \lesssim 10^{-9}$ s. We discuss bounds on $|U_{\mu h}|^2$ obtained from the recent precision measurements with muons and show that they are consistent with the above limits. If the ν_h exists its admixture in the ordinary muon or kaon decay would result in the decay chain $\mu \to e\nu_e\nu_h \to e\nu_e\gamma\nu$ or $K \to \mu\nu_h \to \mu\gamma\nu$, respectively. We propose a new experiment for a sensitive search for these processes in μ and K decays at rest allowing to either definitively confirm or exclude the existence of the ν_h . To our knowledge, no experiment has specifically searched for the signature of radiative decay of massive neutrinos from particles decays as proposed in this work. The search is complementary to the current experimental efforts to clarify the origin of the LSND and MiniBooNE anomalies.

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I. INTRODUCTION

Over the past 10 years there is a puzzle of the 3.8 σ event excess observed by the LSND Collaboration [1]. This excess originally interpreted as a signal from $\overline{\nu}_{\mu} \to \overline{\nu}_{e}$ oscillations was not confirmed by further measurements from the similar KARMEN experiment [2]. The MiniBooNE experiment, designed to examine the LSND effect, also found no evidence for $\nu_{\mu} \rightarrow \nu_{e}$ oscillations. However, an anomalous excess of low energy electronlike events in quasielastic neutrino events over the expected standard neutrino interactions has been observed [3]. Recently, MiniBooNE has reported new results from a search for $\overline{\nu}_{\mu} \to \overline{\nu}_{e}$ oscillations [4]. An excess of events was observed which has a small probability to be identified as the background-only events. The data are found to be consistent with $\overline{\nu}_{\mu} \to \overline{\nu}_{e}$ oscillations in the 0.1 eV² range and with the evidence for antineutrino oscillations from the LSND.

In recent work [5] (see also [6, 7]) it has been shown that these puzzling results could all be explained in a consistent way by assuming the existence of a heavy sterile neutrinos (ν_h). The ν_h is created in ν_μ neutral-current interactions and decay subsequently into a photon and a lighter neutrino ν in the LSND and MiniBooNE detectors, but it cannot be produced in the KARMEN experiment due to the high energy threshold. The ν_h could be Dirac or Majorana type. The ν_h could decay dominantly into a $\gamma\nu$ pair if, for example, there is a large enough transition magnetic moment between the ν_h and ν mass states. Assuming the ν_h is produced through mixing with ν_μ , the combined analysis of the LSND and MiniBooNe excess events suggests that the ν_h mass, mixing strength, and lifetime are, respectively, in the range

$$40 \lesssim m_h \lesssim 80 \text{ MeV}, \ 10^{-3} \lesssim |U_{\mu h}|^2 \lesssim 10^{-2},$$

$$10^{-11} \lesssim \tau_h \lesssim 10^{-9} \text{ s.}$$
 (1)

A detailed discussion of consistency of these values with

the constraints from previous searches for heavy neutrinos [8] is presented in [5]. Briefly, the mixing of (1) is not constrained by the limits from the the most sensitive experiments searched for extra peaks in two-body π, K decays [8], because the ν_h mass range of (1) is outside of the kinematical limits for $\pi_{\mu 2}$ decays, and not accessible to $K_{\mu 2}$ experiments due to experimental resolutions. The parameter space of (1) cannot be ruled out by the results of high energy neutrino experiments, such as NuTeV or CHARM, as they searched for ν_h 's of higher masses $(m_h \gtrsim 200 \text{ MeV})$ decaying into muonic final states $(\mu\pi\nu, \mu\mu\nu, \mu e\nu, ...)$ [8], which are not allowed in our case. The best limits on $|U_{\mu h}|^2$ derived for the mass range (1) from the search for $\nu_h \to e^+e^-\nu$ decays in the PS191 experiment [9], as well as the LEP bounds [10], are found to be compatible with (1) assuming the dominance of the $\nu_h \to \gamma \nu$ decay. New limits on mixing $|U_{\mu h}|^2$ obtained by using the recent results on precision measurements of the muon Michel parameters by the TWIST experiment [11] are also found to be consistent with (1). Finally, the most stringent bounds on $|U_{\mu h}|^2$ coming from the primordial nucleosynthesis and SN1987A considerations, as well as the limits from the atmospheric neutrino experiments, are also evaded due to the short ν_h lifetime.

As mentioned above, the most natural way to allow the radiative decay of heavy neutrino is to introduce a nonzero transition magnetic moment (μ_{tr}) between the ν_h and ν mass states; see e.g. [12, 13]. Such coupling of neutrinos with photons is a generic consequence of the finite neutrino mass. Observations of the neutrino magnetic moment could allow us to distinguish whether neutrinos are of the Dirac or Majorana type since the Dirac neutrinos can only have flavor conserving transition magnetic moments while the Majorana neutrinos can only have a changing one. In addition, Dirac neutrinos can have diagonal magnetic moments while Majorana neutrinos cannot. The nonzero magnetic moment of

the neutrino, although tiny, is predicted even in the standard model (SM). The detailed calculations of the radiative neutrino decay rate in terms of the neutrino masses and mixings were performed long ago, see e.g. [14–16]. The radiative decay mode could even be dominant, if the μ_{tr} value is large enough; see [12, 13]. Originally, the idea of a large (Dirac) magnetic moment ($\gtrsim 10^{-11} \mu_B$, where μ_B is the Bohr magneton) of the electron neutrino has been suggested in order to explain the solar neutrino flux variations [17]. Taking into account that in many extensions of the standard model the value of the μ_{tr} is typically proportional to the ν_h mass, the intention to make the radiative decay of a $\nu_h \lesssim 100 \text{ MeV}$ dominant by introducing a large transition magnetic moment (or through another mechanism) is not particularly exotic from a theoretical viewpoint. Such types of heavy neutrinos are present in many interesting extensions of the standard model, such as GUT, superstring inspired models, left-right symmetric models and others, for a review; see e.g. Ref.[12].

The $\nu_h \to \gamma \nu$ decay rate due to a transition moment μ_{tr} is given by [18]

$$\Gamma_{\nu\gamma} = \frac{\alpha}{8} \left(\frac{\mu_{tr}}{\mu_B}\right)^2 \left(\frac{m_h}{m_e}\right)^2 \left(1 - \frac{m_{\nu}^2}{m_h^2}\right)^3 m_h \tag{2}$$

where $m_{\nu}(< m_h)$, is the mass of the lighter neutrino in the $\nu_h \to \gamma \nu$ decay, $\mu_B = \frac{e}{2m_e}$ is the Bohr magneton, and m_e is the mass of electron. Assuming $m_{\nu} \ll m_h$, and $\tau_h \lesssim 10^{-9}$, which came from the requirement for the $\nu_h \to \gamma \nu$ decays to occur mostly inside the MiniBooNE fiducial volume, results in [5]

$$\mu_{tr} \gtrsim 3.7 \times 10^{-8} \mu_B.$$
 (3)

A detailed discussion of the interpretation of the $\nu_h \to \gamma \nu$ decay in terms of transition magnetic moment and consistency of the value (3) with the constraints from previous experiments is presented in [5] (see, Sec.VI.F). Let us just note, that the ν mass state should not necessarily be the dominant mass state of an ordinary neutrino, ν_e , ν_μ or ν_{τ} . It could be a sterile neutrino as well. In this case, there are no any constraints on the transition magnetic moment between two sterile states at all. There are also no stringent experimental bounds on the μ_{tr} between ν_h and ν , if $\nu = \nu_{\tau}$, because there are no intense τ neutrino beams. First experimental limits on μ_{tr} between a heavy sterile neutrino and muon neutrino have been obtained in Ref.[19], based on the idea of the Primakoff conversion $\nu_{\mu}Z \rightarrow \nu_{h}Z$ of the muon neutrino into a heavy neutrino in the external Coulomb field of a nucleus Z, with the subsequent $\nu_h \to \gamma \nu$ decay. By using the results from the NOMAD experiment [20], a model-independent bound $\mu_{tr}^{\mu h} \lesssim 4.2 \times 10^{-8} \mu_B$ was set for the ν_h masses around 50 MeV (see Table 1 and Fig.2 in Ref.[19]), which is also consistent with Eq.(3).

If the ν_h is indeed a component of ν_{μ} 's, it would be produced by any source of ν_{μ} according to the proper mixing and phase space and helicity factors [13, 21]. In

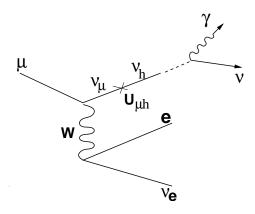


FIG. 1: Schematic illustration of the production and subsequent radiative decay of heavy neutrinos in the ordinary muon decay.

particular, the ν_h could be produced in charge-current weak interactions of muons or kaons. For example, for the mass range of (1) the nonzero mixing $|U_{\mu h}|^2$ would result in the decay $\mu \to e\nu_e\nu_h$. The muon, which is normally decays into an $e\nu_e$ pair and a ν_μ , might instead decay to an $e\nu_e$ pair and a heavy neutrino ν_h which decays subsequently into $\gamma\nu$, as schematically illustrated in Fig. 1.

In this work we show that the recent precision measurement results obtained with muons are consistent with (1), and that the puzzle of the LSND-MiniBooNE excess events could be uniquely resolved by the proposed new experiment on searching for the muon and/or kaon decay chains, $\mu \to e\nu_e\nu_h \to e\nu_e\gamma\nu$ and $K \to \mu\nu_h \to \mu\gamma\nu$, respecively.

II. CONSTRAINTS FROM MUON PROCESSES

For completeness of the analysis of constraints reported in [5], let us examine first the recent precision measurements results obtained with muons. Note that for the mixing and mass regions of (1), the inclusion of the heavy neutrino effect results in the $\mu \to e\nu_e\nu_h$ decay rate which can be well approximated by [21, 22]

$$\Gamma(\mu \to e\nu_e \nu_h) \approx \frac{G_F^2 |U_{\mu h}|^2}{192\pi^3 m_\mu^3} \left[m_\mu^8 - m_h^8 + 8m_h^6 m_\mu^2 - 8m_h^2 m_\mu^6 + 24m_h^4 m_\mu^4 Log(\frac{m_\mu}{m_h}) \right]$$
(4)

and in the corresponding branching fraction

$$B(\mu \to e\nu_e\nu_h) \simeq 10^{-5} - 10^{-3},$$
 (5)

which is in the experimentally accessible range. More detailed calculations of the $\mu \to e\nu_e\nu_h$ decay rate including arbitrary ν_h weak couplings can be found in [23].

Muon lifetime

Very recently, the MuLan Collaboration has reported on measurements of the mean lifetime τ_{μ} of positive muons to a precision of 0.6 ppm [24]. Using the new world average, $\tau_{\mu} = 2.1969803(22) \,\mu \text{s}$ and the relation between the muon lifetime and the Fermi constant $G_F \tau_{\mu}^{-1} =$ $\frac{G_F^2 m_\mu^5}{192\pi^3}(1+\Delta)$, where Δ is the sum of phase space, QED and hadronic corrections, results in new determination of the Fermi constant $G_F^{\mu} = 1.1663788(7) \times 10^{-5} \; \mathrm{GeV}^{-2}$ to a precision of 0.6 ppm [24]. The mixing of the ν_h into ν_{μ} would decrease the determined value of G_F^{μ} . To estimate the allowed contribution from the $\mu \to e\nu_e\nu_h$ decay, one could compare the experimentally measured muon decay rate to a predicted one, by using G_F' extracted from another measurements which are not directly affected by the contribution from heavy neutrino. One possible way is to use the pure leptonic decay rate of the tau $\Gamma(\tau \to e\nu_e\nu_\tau)$, which provides the corresponding Fermi constant $G_F^{\tau e}=1.1668(28)\times 10^{-5}~{\rm GeV^{-2}}$ [8]. Comparing it with MuLan values for G_F one finds $\Delta G_F = \hat{G}_F^{\tau e} - \tilde{G}_F^{\mu} < 5 \times 10^{-3} \ GeV^{-2} \ (90\% C.L.)$. Taking into account (4) leads to the bound $|U_{\mu h}|^2 < 8 \times 10^{-3}$, which is consistent with (1). One can also use a number of indirect prescriptions for extracting of precise values of G_F [25]. For example, one can define $G_F' = \frac{4\pi\alpha}{\sqrt{2}m_Z^2\sin^22\Theta_W(m_Z)(1-\Delta r)}$ where Θ_W , m_Z and Δr are the Weinberg angle, the mass of the Z gauge bosons extracted from the precision measurements at LEP, and a factor for radiative corrections, respectively. Using the values of Θ_W , m_Z and Δr reported in [25], one can ob- $\label{eq:GF} \mbox{tain } G_F' = 1.1672 (\pm 0.0008) \left(\begin{array}{c} +0.0018 \\ -0.0007 \end{array} \right) \times 10^{-5} \; GeV^{-2}.$ Comparing it with G_F^{μ} and adding statistical and systematic errors in quadrature, one finds at 90% CL, $\Delta G_F = G_F' - G_F^{\mu} < 4.1 \times 10^{-3} \ GeV^{-2}$ (90% C.L.), which leads to the bound $|U_{\mu h}|^2 < 7 \times 10^{-3}$, which is also consistent

with (1).

Rare muon decays

As the final states of the decay $\mu \to e\nu_e\nu_h \to e\nu_e\gamma\nu$ and the radiative muon decay $\mu \to e\nu_e\nu_\mu\gamma$ are identical, the decay rate of the former can be constrained from the precise measurements of the branching fraction $B(\mu \to e \nu_e \nu_\mu \gamma)$ of the later. The most precise measurements of the radiative muon decay are reported by the PI-BETA Collaboration [26]. The measured branching fraction $B_{exp}(\mu \to e\nu_e\nu_\mu\gamma) = (4.4 \pm 0.1) \times 10^{-3}$ is in a good agreement with the predicted value $B_{SM}(\mu \to e\nu_e\nu_\mu\gamma) =$ 4.3×10^{-3} for the photon energy $E_{\gamma} > 15$ MeV, and the $e - \gamma$ opening angle $\Theta_{e\gamma} > 45^{\circ}$. Thus, the contribution from the decay $\mu \to e\nu_e\nu_h$ is allowed to be at the level $|B_{exp}(\mu \to e\nu_e\nu_\mu\gamma) - B_{SM}(\mu \to e\nu_e\nu_\mu\gamma)| \simeq (1.0 \pm 1.0) \times$ ⁴, which, taking into account the efficiency for the above selection criteria, results for the ν_h mass range (1)

in the 2σ limit $B(\mu \to e\nu_e\nu_h) \lesssim (2.6-4.1)\times 10^{-4}$, which is consistent with (5). Interestingly, for the large values of $\Theta_{e\gamma}$, which are expected for the $\mu \to e\nu_e\nu_h \to e\nu_e\gamma\nu$ events, PIBETA has observed an excess of misidentified nonradiative events attributed to the so-called "splashback" events [26]. The size of this effect is comparable with (5). It was assumed that these rare events originated probably from Michel decays when the shower component of the decay electron entering an electromagnetic calorimeter is emitted at a very large angle with respect to the primary electron momentum direction.

The decay chain $\mu \to e\nu_e\nu_h \to e\nu_e\gamma\nu$ could also contribute to the background for the lepton flavor violating decay $\mu \to e \gamma$ whose branching fraction is constrained to be $B_{exp}(\mu \to e\gamma) < 1.2 \times 10^{-11}$ by the MEGA experiment [27]. In this experiment, to avoid background from the radiative muon decay, only back-to-back $e\gamma$ pairs were selected for analysis. The energy of the electron was required to be around the end point of $E_e = 52.8 \text{ MeV}$ within the energy resolution of 0.23 MeV [27]. Because the maximal allowed electron energy in the decay $\mu \rightarrow$ $e\nu_e\nu_h$ is significantly less, $E_e^{max}=(m_\mu^2-m_{\nu_h}^2)/2m_\mu<44$ MeV, this potential background decay mode was rejected by the above selection criteria.

Muon capture

Recently, bounds on $|U_{\mu h}|^2$ have been obtained from the measurements of the radiative muon capture rate on hydrogen, $\mu p \to \nu_{\mu} n \gamma$, for the γ energy threshold of $E_{\gamma} >$ 60 MeV [28] (see also [29]). The new limits seem are in tension with $|U_{\mu h}|^2$ values from (1), although their exclusion strength is a factor of few. For ν_h masses from 40 to 70 MeV the limits are, respectively, from $|U_{\mu h}|^2 \lesssim$ $7 \cdot 10^{-4}$ to $|U_{\mu h}|^2 \lesssim 5 \cdot 10^{-4}$ (Fig. 4, a = 1 in [28]), while the corresponding 2σ lower bounds of the allowed LSND-MiniBooNE parameter region (Fig. 24, a=-1 in [5]) are in the range from $|U_{\mu h}|^2 \gtrsim 2 \cdot 10^{-3}$ to $|U_{\mu h}|^2 \gtrsim 3 \cdot 10^{-3}$ (In Ref.[28] the definition of sign of the asymmetry parameter a of the photon angular distribution in the rest frame is opposite to the one in [5]). However, the more conservative 3 σ LSND-MiniBooNE lower bounds for the same mass range are calculated to be, respectively, from $|U_{\mu h}|^2 \gtrsim 4 \cdot 10^{-4}$ to $|U_{\mu h}|^2 \gtrsim 5 \cdot 10^{-4}$, and the tension is not apparent. Furthermore, regardless of the level of the exclusion strength, there is also a direct way to evade the radiative muon capture limit by shifting the photon energy spectrum from the $\nu_h \to \gamma \nu$ decay towards the lower energy region below 60 MeV by allowing the neutrino ν to be massive enough, as suggested in [28].

III. EXPERIMENTS TO SEARCH FOR THE $\nu_h \to \gamma \nu \; \mathbf{DECAY}$

In order to (dis)prove the ν_h interpretation of the LSND-MiniBooNE excess events, we propose a new ex-

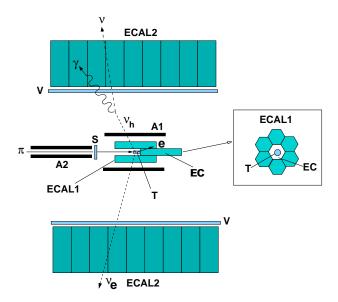


FIG. 2: Schematic illustration of the proposed beam-dump type experiment to search for the decay $\mu^+ \to e^+ \nu_e \nu_h \to$ $e\nu_e\gamma\nu$. Shown are the beam defining scintillator counter S, the active target T surrounded by the electromagnetic calorimeters ECAL1 and ECAL2, and the ECAL1 endcap counter EC used as a light guide for the light produced in the target. The source of muons is the $\pi \to \mu + \nu$ decay at rest in T. Electrons and photons from the ordinary muon decays $\mu^+ \to e^+ \nu_e \nu_\mu(\gamma)$ are dumped in the assembly, consisting of the ECAL1 and a lead absorber A1, used as a shield for the ECAL2. Electrons and γ 's from the π , μ decays in flight before the S counter are absorbed by the shield A2. The ν_h produced through the mixing with the muon neutrino penetrates the (ECAL1+ A1)-assembly and decays in flight in the free space between the ECAL1 and ECAL2 into a light neutrino and photon, which is detected by the ECAL2. The insert shows the front view of the ECAL1 area.

periment to search for the $\nu_h \to \gamma \nu$ decay chain from the muon or kaon decays at rest with a sensitivity in $|U_{\mu h}|^2$ several orders of magnitude higher than the $|U_{\mu h}|^2$ values of (1).

A. Search for the $\mu \to e\nu_e\nu_h \to e\nu_e\gamma\nu$ decay

The main components of the detector are schematically shown in Fig. 2. A beam of positive pions with momentum of $\simeq 70~{\rm MeV/c}$, e.g. from the $\pi{\rm M3}$ pion beam line at PSI, , defined by a scintillator counter S, is stopped in an active target (T) instrumented with energy deposition and time readout. The source of muons is the $\pi \to \mu + \nu$ decay at rest in T. The target T is surrounded by an almost 4π hermetic shield consisting of an electromagnetic calorimeter ECAL1 and a lead absorber (A1), where all the electrons and photons from the π , μ decays in T are dumped. The ECAL1 is surrounded by another ECAL2 to detect photons from the $\nu_h \to \gamma \nu$ decays in flight. It is assumed that the ν_h produced via the mixing in the $\mu \to e\nu_e\nu_h$ decay is a weakly

interacting particle, which penetrates the (ECAL1+A1) assembly without significant attenuation and decays subsequently in the free space between the calorimeters, as shown in Fig. 2. Electrons and γ 's from the π , μ decays in flight before the S counter, cannot hit the ECAL2, as they are absorbed by the shield A2. The experimental signature of the decay chain $\mu \to e\nu_e\nu_h \to e\nu_e\gamma\nu$ is two signals of the energy deposition in the calorimeters separated in time by an interval $\Delta t \lesssim 1$ ns corresponding to the ν_h time-of-flight. The physical background for the signal events is expected to be very small, because only neutrinos can penetrate the shield, but they produce a negligible number of events in the ECAL2. As the proposed experiment is of the beam-dump type, there is no special requirements for the purity of the beam. The amount of muons and electrons from π decays in flight could be comparable to the number of pions at the end of the beam line.

To estimate the sensitivity of the proposed experiment a feasibility study based on simplified Monte Carlo simulations, similar to the one described in [30], has been performed. The pions are stopped in the T, which is a plastic scintillator with a diameter of 5-10 mm and a height of 10 mm. According to simulations the decay muon came to rest passing about 1 mm in T and depositing about 4.2 MeV in the T, which can be used for its identification. The ECAL1, is an array of 7 BGO counters, as schematically shown in Fig. 2, each of 55 mm in diameter and 220 mm long, which were previously used in the PSI experiment on precise measurements of the π_{e2} decay rate [31]. The ECAL2 is an array of the same counters with electron energy resolution of $\simeq 2.5\%$ at 50 MeV. The readout of the energy deposition in the ECAL2 is triggered by a tag signal of the electron appearance from the decay chain $\pi \to \mu \to e + anything$, which is defined by a coincidence of a signal from a stopped pion, a delayed signal from the stopped decay muon and a delayed signal from the ECAL1. The light signals produced in T could be readout through the ECAL1 endcap crystal (EC) which acts as a light guide as shown in Fig. 2. The T signals could be distinguished from the EC signals due to their significantly different decay times by using the technique described in detail in Ref.[32].

The significance of the ν_h discovery in the proposed experiment scales as $S=2(\sqrt{n_s+n_b}-\sqrt{n_b})$, where n_s , n_b are the number of detected signal and background events [33]. The number of events expected from the $\mu \to e\nu_e\nu_h \to e\nu_e\gamma\nu$ decay chain is calculated as

$$n_s \simeq n_\mu B(\mu \to e \nu_e \nu_h) B(\nu_h \to \gamma \nu) P_{\nu_h \to \gamma \nu} f_\gamma \epsilon_\gamma t,$$
 (6)

where n_{μ} is the muon stop rate in the target, $B(\nu_h \to \gamma \nu) \simeq 1$ [5], $P_{\nu_h \to \gamma \nu} \simeq exp(-l/c\gamma \tau_h)$ is the probability for the ν_h to decay in flight in free space, where l is an effective (ECAL1+A) thickness and $\gamma \simeq 1$ is the gammafactor of the ν_h , $f_{\gamma} \gtrsim 0.8$ is the fraction of events with the energy deposition in the ECAL2 > 10 MeV, $\epsilon_{\gamma} \simeq 0.1$ is the average γ detection efficiency, and t is the running time. Simulations show that the energy spectrum of de-

cay photons is well above $\simeq 10$ MeV for the ν_h masses of (1) and a wide range of the ν masses. To estimate n_b , the following background sources are considered: (i) the radiative π/μ decays, which have the branching fraction $\simeq 10^{-2}$ for $E_{\gamma} \gtrsim 10$ MeV [8]. To suppress this background the effective thickness of the (ECAL1+A1)assembly is selected to be $l \gtrsim 16~X_0$ resulting in $\lesssim 10^{-8}$ decay photons per pion stop penetrating the shield without interactions: (ii) bremsstrahlung of decay electrons in the ECAL1 results in a leak of low energy photons to the ECAL2, which can be rejected by the energy cut $E_{\gamma} \gtrsim 10$ MeV; (iii) accidental γ 's from π , μ radiative decays in flight are rejected by the shield A2 and by the requirement to have only one entering particle for a particular event. The number of γ 's from the $\mu \to e\nu_e\nu_\mu\gamma$ decays scattered in the S counter is found to be small; (iv) accidental coincidences from cosmic rays can be removed by an active veto and can be neglected; (v) the neutron background is expected to be small, as the setup could be located at a large ($\gtrsim 30$ m) distance from the proton target. Finally, we found that the expected background rate $n_b \lesssim 10^{-8}/\pi$ decay is dominated by (i), and is well controlled by the choice of the absorber A1 thickness. Assuming $S \gtrsim 5$ and the muon stop rate $n_{\mu} \simeq 3 \cdot 10^4 \ \mu/s$ one could expect the sensitivity in the $\mu \to e\nu_e\nu_h$ decay branching ratio as small as $B(\mu \to e\nu_e\nu_h) \lesssim 10^{-9}$ for the beam exposure $\simeq 1$ month.

In the case of signal observation, the value of the ν_h mass can be evaluated from the end point of the γ -energy spectrum. To cross check the origin of signal events, one could use an additional shield in the space between the ECALs to absorb a fraction of photons from the $\nu_h \to \gamma \nu$ decays in flight, which can be well predicted. If no signal events are observed, the limit on the mixing strength:

$$|U_{\mu h}|^2 \lesssim 10^{-8} e^{0.3/\tau_h[ns]} \left[1 - \frac{m_h}{m_\mu}\right]^{-7/2}$$
 (7)

could be set as a function of the ν_h mass and lifetime. Using (7), one can see that for the mass range of (1) and lifetime values in the range $5\cdot 10^{-11}\lesssim \tau_h\lesssim 10^{-9}$ s the limits on the mixing strength are $|U_{\mu h}|^2\lesssim 10^{-7}-10^{-4}$ and hence, the $|U_{\mu h}|^2$ values of (1) would be firmly excluded. The choice of the (ECAL1+A1)-assembly thickness compromises the rejection factor of background γ 's from the $\mu\to e\nu_e\nu_\mu\gamma$ decay and the sensitivity in $|U_{\mu h}|^2$. For the lifetimes as short as $\tau_h\lesssim 5\cdot 10^{-11}$ s the vast majority of ν_h 's decays in the vicinity of the target and the limit is less restrictive. To improve sensitivity for this lifetime region, one could replace the ECAL1 with an assembly of thin plastic scintillator counters to detect decay electrons and the A1 with an absorber made of a higher-Z material, e.g. tungsten, such that the overall thickness of the shield is reduced to a few centimeters.

B. Search for the $K \to \mu\nu_h \to \mu\gamma\nu$ decay

A similar search for the ν_h can also be performed with another experiment, analogous to the one discussed above. In this experiment we propose to search for the $K \to \mu\nu_h \to \mu\gamma\nu$ decay chain from kaon decays at rest. The main component of the detector are the same as shown in Fig.2, but the incident beam is composed mainly of positive kaons. The tag for the two-body $K \to \mu\nu$ decay is the energy deposition around maximal value of 150 MeV in the ECAL1 from the stopped muon kinetic energy, which is expected for the neutrino masses from 0 to 80 MeV. Similar to the above muon experiment, the experimental signature of the $K \to \mu\nu_h \to \mu\gamma\nu$ decay is two signals of the energy deposition in the calorimeters ECAL1 and ECAL2 separated in time by the time interval $\Delta t \lesssim 1$ ns corresponding to the ν_h time-of-flight. The number of $K \to \mu \nu_h$ events is defined by the mixing $|U_{\mu h}|^2$ and by the phase space and helicity factors which depend on the ν_h mass [34]. For the mass interval $m_{\nu_h} \simeq 40-80$ MeV the chirality-flip is mostly due to the sterile neutrino mass which results in

$$\Gamma(K \to \mu \nu_h) \approx \Gamma(K \to \mu \nu_\mu) |U_{\mu h}|^2 \rho \left(\frac{m_{\nu_h}^2}{m_\mu^2}\right),$$
 (8)

where term $\rho\left(\frac{m_{\nu_h}^2}{m_{\mu}^2}\right)$ includes both phase space and helicity factors [34]. Using (8), we find that the branching fraction of $K \to \mu\nu_h$ is in the experimentally accessible range:

$$Br(K \to \mu \nu_h) \simeq 10^{-3} - 10^{-2}$$
 (9)

for heavy neutrino masses in the range 40 - 80 MeV. Assuming the kaon stopping rate $n_K \simeq 3 \cdot 10^4~\mu/s$ one could expect the sensitivity in the $K \to \mu \nu_h$ decay branching ratio as small as $B(K \to \mu \nu_h) \lesssim 10^{-9}$ for the beam exposure $\simeq 1$ month. The expected sensitivity of the kaon experiment is comparable with (7), however for the ν_h lifetime values $\lesssim 10^{-10}$ s it is even higher due to the higher energy of ν_h 's, and, thus the longer ν_h decay length. This gives an advantage for searching for the short-lived ν_h in K decays compare to the muon experiment.

C. Search for the $\mu \to e \nu_e \nu_h \to e \nu_e \gamma \nu$ decay with cosmic muons

Finally, note that a search for the $\mu \to e\nu_e\nu_h \to e\nu_e\gamma\nu$ decay events may also be possible with existing cosmic muon data accumulated by large Cherenkov neutrino detectors, such as SuperK [35], MiniBooNE [36], etc.. The idea is to search for an excess of $e-\gamma$ events from stopped cosmic muon decays, which are characterized by a clean Cherenkov ring from the electron from muon decay and the well separated ring from a Compton-scattered electron from the gamma from heavy neutrino decay [37]. The photon spectrum from the radiative muon decay

drops quckly with photon energy ($\simeq 1/E_{\gamma}$), therefore, one would expect a low background level in the signal region of $E_{\gamma} \gtrsim 20-30$ MeV and large opening angle $\Theta_{e\gamma} \gtrsim 30^{\circ}$. However, as the ν_h decay length ($\lesssim 30$ cm) is significantly less than the effective photon Comptonscattering length ($\simeq 60 \text{ cm}$), both the signal and "splashback" background events, discussed in Sec. II B, are expected to have similar spatial distributions with respect to the primary decay vertex. Thus, one cannot effectively suppress these background events by using spatial cuts. The use of cuts only on the photon or the sum of the electron and associated photon energy deposition can not be efficient enough, in particular, due to a moderate energy resolution of Cherenkov detectors in the 10 - 50 MeV energy range, e.g. $\simeq 15\%$ at 53 MeV in MiniBooNE [36]. An estimate of the sensitivity of such an experiment requires detailed simulations, which itself might be inaccurate in this extreme "splashback" regime. This is beyond the scope of this work.

A search for $\mu \to e\nu_e\nu_h \to e\nu_e\gamma\nu$ events could also be performed by the ICARUS [38]. In this experiment the decay electrons energy spectrum from a sample of stopping cosmic muon events recorded during the test run of the ICARUS T600 detector was studied. The detector allows the spatial reconstruction of the events with fine granularity, hence, the precise measurement of the range and dE/dx of particles with high sampling rate. The measured energy (E_{exp}) resolution for electrons below 50 MeV is finally extracted from the simulated (E_{sim}) sample, obtaining $(E_{exp} - E_{sim})/E_{sim} =$ $2\% + 11\%/E^{0.5}[MeV]$. The detector has good spatial and energy resolution, and is capable of distinguishing between electron and photons, hence, a better sensitivity for the search for $\mu \to e\nu_e\nu_h \to e\nu_e\gamma\nu$ events can be expected from the analysis of recorded data.

Very recently, another interesting idea of searching for ν_h 's has been proposed [39]. It has been noticed that a copious production of ν_h 's from K decays in flight could

occur in air showers. Taking this into account, a sensitive search for signals from subsequent ν_h radiative decays in neutrino telescopes, like ANTARES or the DeepCore in IceCube, could be performed.

IV. SUMMARY

In summary, we showed that the recently proposed explanation of the puzzle from the LSND, KARMEN and MiniBooNE experiments in terms of the radiative decay of a 40-80 MeV sterile neutrino, could be uniquely probed by the proposed new experiment on direct search for this decay in the muon and/or kaon decays at rest with the sensitivity in a corresponding branching fraction as small as a few parts in 10^9 . The quoted sensitivity could be obtained with the proposed setup optimized for several of its properties, such as the absorber A1 thickness, during a month of data taking and would allow us to either confirm or rule out the existence of the ν_h . Two different designs could be implemented for muon experiment to cover the range of the lifetime values $10^{-11} - 10^{-9}$. The proposed searches are complementary to the current experimental efforts to clarify the origin of the excess events observed by the LSND and MiniBooNE experiments. This enhance motivation for the proposed experiments to be performed in the near future. To our knowledge, no experiment has specifically searched for the signature of radiative decay of massive neutrinos from muon or kaon decays as proposed in this work. The search for events from the $\nu_h \to \gamma \nu$ decay can also be performed by using the existing cosmic muon data, collected by neutrino detectors such as SuperK [35], MiniBooNE [36], ICARUS [38], as well as in neutrino telescopes [39].

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